TELEOPERATION, TELEROBOTICS

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INTRODUCTION

In a general sense, teleoperator devices enable human operators to remotely perform mechanical actions that usually are performed by the human arm and hand. Thus, teleoperators, or the act of teleoperation, extends the manipulative capabilities of the human arm and hand to remote, physically hostile, or dangerous environments. In this sense, teleoperation conquers space barriers in performing manipulative mechanical actions at remote sites, like telecommunication conquers space barriers in transmitting information to distant places.

Historically, teleoperator systems were developed in the mid- 1940s to create capabilities for handling highly radioactive material. Teleoperators allowed a human operator to handle radioactive material from a workroom separated by a one meter thick, radiation-absorbing concrete wall from the radioactive environment. The operator could observe the task scene through radiation resistant viewing ports in the wall. The development of teleoperators for the nuclear industry culminated in the introduction of bilateral force-reflecting master-slave manipulator systems. In these very successful systems, the slave arm at the remote site is mechanically or electrically coupled to the geometrically identical or similar master arm handled by the operator and follows the motion of the master arm. The coupling between the master and slave arms is a two-way coupling: inertia or work forces exerted on the slave arm can back-drive the master arm, enabling the operator to feel the forces that are acting on the slave arm. Force information available to the operator is an essential requirement for dexterous control of remote manipulators, since general-purpose manipulation consists of a series of well-controlled contacts between handling device and objects and also implies the transfer of forces and torques from the handling device to objects.

In a more modern point of view, teleoperators are specialized robots, called telerobots, performing manipulative mechanical work remotely where humans cannot go or do not want to go. Teleoperator robots serve to extend, through mechanical, sensing, and computational techniques, the human manipulative, perceptive, and cognitive abilities into an environment that is either hostile to or remote from the human operator. Teleoperator robots or, in today's terminology, telerobots typically perform non-repetitive or singular, servicing, maintenance or repair work under a variety of environmental conditions ranging from structured to unstructured conditions.

Telerobot control is characterized by a direct involvement of the human operator in the control since, by definition of task requirements, teleoperator systems extend human manipulative, perceptual and cognitive skills to remote places.

Continuous human operator control in teleoperation has both advantages and disadvantages. The main advantage is that overall task control can rely on human perception, judgement, decision, dexterity, and training. The main disadvantage is that the human operator must cope with a sense of remoteness, be alert to and integrate many information and control variables, and coordinate the control of one or two mechanical arms each having many (typically six) degrees of freedom—

and doing all these with limited human resources. Furthermore, in many cases like space and deep sea applications, communication time delay interferes with continuous human operator control.

Modern development trends in teleoperator technology are aimed at amplifying the advantages and alleviating the disadvantages of the human element in teleoperator control by the development and the use of advanced sensing and graphics displays, intelligent computer controls, and new computer-based human-machine interface devices and techniques in the information and control channels. The use of model and sensor data driven automation in teleoperation offers significant new possibilities to enhance overall task performance by providing efficient means for task-level controls and displays.

In the subsequent part of this chapter subsection, we will focus on mechanical, control and display topics that are specific to the human-machine system aspect of teleoperation and telerobotics: hand controllers, task-level manual and automatic controls, and overlaid, calibrated graphics displays aimed to overcome telecommunication time delay problems in teleoperation. Experimental results also will be briefly summarized.The subsection will conclude with specific issues in anthropomorphic telerobotics and with a brief outline of emerging new application areas.

HAND CONTROLLERS

The human arm and hand are functionally both powerful mechanical tools and delicate sensory organs through which information is received and transmitted to and from the outside world. Therefore, the human arm-hand system (thereafter simply called hand here) is a key communication medium in teleoperator control. With hand actions, complex position, rate, or force commands can be formulated to control a remote robot arm-hand system in all workspace directions. At the same time, the human hand also can receive contact force, torque and touch information from the remote robot hand or end effector. Furthermore, the human fingers provide capabilities to convey new commands to a remote robot system from a suitable hand controller. Hand-controller technology is, therefore, an important component technology in the development of advanced teleoperators. Its importance is particularly underlined when one considers computer control which connects the hand controller to a remote robot arm system.

Here we review teleoperator system design issues and performance capabilities from the viewpoint of the operator's hand and hand controllers through which the operator exercises manual control communication with remote manipulators. Through a hand controller, the operator can very physically "write" commands to and also "read" information from a remote manipulator in real time. In this sense, it is conceptually appropriate and illuminating to view the operator's manual control actions as a control "language" and, subsequently, to consider the hand controller as a "translator" of that control language to machine-understandable control actions.

A particular property of manual control as compared to computer keyboard type control in teleoperation is that the operator's hand motion, as translated by the hand controller, directly describes a full trajectory to the remote robot arm in the time continuum. In the case of a position control device, the operator's manual motion contains direct position, velocity, acceleration, and even higher order derivative motion command information. In the case of a rate input device, the position information is indirect since it is the integral of the commanded rate, but velocity, acceleration and even higher order derivative motion command information is direct in the time continuum. All this direct operator hand motion relation to the remote robot arm's motion behavior in real time through the hand controller is in sharp contrast to the computer keyboard type commands which, by their very nature, are symbolic and abstract, and require the specification of some set of parameters within the context of a desired motion.

First, a brief survey of teleoperator hand controller technology will be presented covering both hand grips and complete motion control input devices as well as the related control modes or strategies. Then a specific example, a general purpose force-reflecting position hand controller will be briefly discussed, implemented and evaluated at the Jet Propulsion Laboratory (JPL), including a novel switch module attached to the hand grip.

A. *Control Handles*

The control handles are hand grips through which the operator's hand is physically connected to the complete hand controller device. Fourteen basic handle concepts have been considered and evaluated in [1]: (i) Nuclear Industry Standard Handle; it is a squeeze grasp gripper control device which exactly simulates the slave end effector squeeze-type grasp motion. (ii) Hydraulic Accordion Handle; it is a finger-heel grasp device using a linear motion trigger driven by hydraulic pressure. (iii) Full-length Trigger; it is a fingerheel type, linear motion gripper control device driven by a mechanism. (iv) Finger Trigger; it is a linear or pivoted gripper control device which only requires one or two fingers for grasp actuation. (v) Grip Ball; it is a ball-shaped handle with a vane-like protuberance which prevents slippage of the ball when sandwiched between two fingers. (vi) Bike Brake; it is a finger-heel-type grasp control device in which the trigger mechanism is pivoted at the base of the handle. (vii) Pocket Knife; similar to the above bike brake, but here the trigger mechanism is pivoted at the top of the handle. (viii) Pressure Knob; it is a unibody ball-shaped handle consisting of a rigid main body and a semi-rigid rubber balloon gripper control driven by hydraulic pressure. (ix) T-Bar; it is a one-piece T-shaped handle with a thumb button for gripper control. (x) Contoured Bar; it is a one-piece contoured T-type handle with gripper control surface located on the underside. (xi) Glove; it is a mechanical device which encases the operator's hand. (xii) Brass Knuckles; it is a two-piece T-type handle in which the operator's fingers slip into recesses or holes in the gripper control. (xiii) Door Handle; it is a C-shaped handle with a thumb button gripper control. (xiv) Aircraft Gun Trigger; it is a vertical implementation handle using a lateral grasp for trigger control combined with wrap-around grasp for firm spatial control. For some concept details of the fourteen handles, see Fig 8.1.

The fourteen handle concepts have been evaluated based on ten selection criteria which have been grouped into four major categories as described below.

1) *Engineering development:* This category considers the handle's developmental requirements in terms of (i) design simplicity, (ii) difficulty of implementation, (iii) extent to which a technological base has been established, and (iv) cost.

2) *Controllability:* This category considers the operator's ability to control the motion of the slave manipulator through the handle. Two major categories were used as selection criteria: (i) stimulus-response compatibility and (ii) cross coupling between the desired arm motion/forces and the grasp action. The first category, stimulus-response compatibility, considers the extent to which the handle design approaches the stimulus-response compatibility of the industry standard. This category only considers the desirability of a stimulus-response compatibility from a motion-in/ motion-out standpoint; it does not take into account its effect on fatigue (fatigue is considered in category 4). The second category, cross coupling, considers the extent of cross coupling between the motion or force being applied to the arm and the desired motion or force of the gripper.

3) *Human-handle interaction:* This category considers the effects of the interface and the interaction between the human and the handle. Four major categories were used as selection criteria: (i) secondary function control, (ii) force-feedback ratio, (iii) kinesthetic feedback, and (iv) accidental activation potential. The first category, secondary function,control, considers the appropriateness of secondary switch placement from the standpoint of the operator's ability to activate a given function. The second category, force feedback, considers the extent to which the remote forces must be scaled for a given handle configuration. The third category rates the degree of kinesthetic feedback, particularly with regard to the range of trigger motion with respect to an assumed 3-inch

open/close motion of the end effector. The fourth category deals with the potential for accidental switch activation for a given design. The lower the rating, the more potential exists for accidental activation.

4) Human limitations: This category considers the limitations of the operator as a function of each design (assuming a normalized operator). Two areas were of concern in the handle selection: (i) endurance capacity and (ii) operator accommodation. The first category deals with the relative duration with respect to the other handle configurations during which an operator can use a given design without fatiguing or being stressed. The second category considers the extent to which a given design can accommodate a wide range of operators.

Details of subjective ratings for each of the fourteen handle concepts based on the four categories of criteria can be found in [1]. The value analysis is summarized in Table 8.1. As seen in this table, the finger-trigger-type design stands out as the most promising handle candidate. From a simple analysis it also appears that the most viable technique for controlling a trigger d.o.f. while simultaneously controlling six spatial d.o.f.'s through the handle holding should obey the following guidelines:

- The handle must be held firmly with at least two fingers and the heel of the hand at all times to adequately control the six spatial DOF's,
- At least one of the stronger digits of the hand (i.e., thumb or index finger) must be dedicated to the function of trigger actuation and force feedback; that is, it must be independent of spatial control functions,
- The index finger, having restricted lateral mobility, makes a good candidate for single-function dedication since it cannot move as freely as the thumb from one switch to another, and
- Likewise, the thumb makes a better candidate for multiple switch activation.

B. *Control Input Devices*

Twelve hand controllers have been evaluated for manual control of six d.o.f. manipulators in [1]. Some descriptive details of their designs and their detailed evaluation can be found in [1]. Here we only summarize their basic characteristics.

1) Switch controls: They generally consist of simple spring-centered, three-position (-, off, +) discrete action switches, where each switch is assigned to either a particular manipulator joint or to end effector control.

2) Potentiometer controls: Here, potentiometers are used for proportional control inputs for either position or rate commands. They can be either force-operated (e.g., spring centered) or displacement-operated. Typically, each pot is assigned to one manipulator joint and to end effector control.

3) Isotonic joystick controller: It is a position operated fixed-force (= isotonic) device used to control two or more d.o.f.'s from one hand within a limited control volume. A trackball is a well known example.

4) Isometric joystick controller. It is a force-operated minimal-displacement (= isometric) device used to control two or more d.o.f.'s from one hand from a fixed base. Its command output directly corresponds to the forces applied by the operator, and drops to zero unless manual force is maintained.

5) Proportional joystick controller: It is a single-handed, two or more d.o.f. device with a limited operational volume in which the displacement is a function of the force applied by the operator ($F = kx$), and the command output directly corresponds to the displacement of the device.

6) Hybrid joystick controller: It is composed of isotonic, isometric, and proportional elements (which are mutually exclusive for a given d.o.f.), used to control two or more d.o.f.'s within a limited control volume with a single hand. There are two basic implementation philosophies: concurrent and sequential. In the concurrent implementation, some d.o.f.'s are position-operated and some are force-operated (either isometrically or proportionally). In the sequential implementation, position and force inputs are switched for any d.o.f. For details of these two implementations see [1].

7) Replica controller: It is a device which has the same geometric configuration as the controlled manipulator but built on a different scale. Hence, there is a one-to-one correspondence between replica controller and remote manipulator joint movements without actual one-to-one spatial correspondence between control handle and end effector motion.

8) Master-slave controller: It is a device which has the same geometric configuration and physical dimensions as the controlled manipulator. Consequently, there is a one-to-one correspondence between master and slave arm motion. These and the replica devices can be unilateral (no force feedback) or bilateral (with force feedback) in the implementation.

9) Anthropomorphic controller: It is a device which derives the manipulator control signals from the configuration motion of the human arm. The device may or may not have a geometric correspondence with the remotely controlled manipulator.

10) Nongeometric analogic controller: It is a device which does not have the same geometric configuration as the controlled manipulator, but which maintains joint-to-joint or spatial correspondence between the controller and the remote manipulator.

11) Universal force-reflecting hand controller: It is a six d.o.f. position control device which, through computational transformations, is capable of controlling the end effector motion of any geometrically dissimilar manipulator and can be backdriven by forces sensed at the base of the remote manipulator's end effector (i.e., it provides force feedback to the operator). For more details of this device, see the next section C.

12. *Universal floating-handle controller:* It is a nongeometric six d.o.f. control device, without joints and linkages, which is used for controlling the slave arm end effector motion in hand-referenced control. It can be either unilateral or bilateral in the control mode. A unilateral version of this device is, e.g., a data glove.

C. Universal Force-Reflecting Hand Controller (FRHC)

In contrast to the standard force-reflecting master-slave systems, a new form of bilateral, force-reflecting manual control of robot arms has been implemented at JPL. It is used for a dual arm control setting in a laboratory work cell to carry out performance experiments.

The feasibility and ramifications of generalizing the bilateral force-reflecting control of master-slave manipulators has been under investigation at JPL for more than ten years. Generalization means that the "master arm" function is performed by a "universal" force reflecting hand controller which is dissimilar to the "slave arm" both kinematically and dynamically. The hand controller under investigation is a backdrivable six-degree-of freedom isotonic joystick. It controls a six-degree of-freedom mechanical arm equipped with a six dimensional force-torque sensor at the base of the mechanical hand. The hand controller provides position and orientation control for the mechanical hand. Forces and torques sensed at the base of the mechanical hand back-drive the hand controller so that the operator feels the forces torques acting at the mechanical hand while he controls the position and orientation of the mechanical hand.

The overall schematic of the six-degree-of freedom force-reflecting hand controller employed in the study is shown in Fig.8.2. (The mechanism of the hand controller was designed by J.K. Salisbury, Jr., now at MIT, Cambridge, MA.) The kinematics and the command axes of the hand controller are shown in Fig 8.3.

The hand grip is supported by a gimbal with three intersecting axes of rotation (β_4, β_5, β_6). A translation axis (R_3) connects the hand gimbal to the shoulder gimbal which has two more intersecting axes (β_1, β_2). The motors for the three hand gimbal and translation axes are mounted on a stationary drive unit at the end of the hand controller's main tube. This stationary drive unit forms a part of the shoulder gimbal's counterbalance system. The moving part of the counterbalance system is connected to the R_3, translation axis through an idler mechanism which moves at one half the rate of R_3. It serves (i) to maintain the hand controller's center of gravity at a fixed point and (ii) to maintain the tension in the hand gimbal's drive cables as the hand gimbal changes its distance from the stationary drive unit. The actuator motors for the two shoulder joints are mounted to the shoulder gimbal frame and to the base frame of the hand controller, respectively.

The self-balance system renders the hand controller neutral against gravity. Thus, the hand controller can be mounted both horizontally or vertically, and the calculation of motor torques to back-drive the hand controller does not require gravity compensation.

In general, the mechanical design of the hand controller provides a dynamically "transparent" input/output device for the operator. This is accomplished by low backlash, low friction and low effective inertia at the hand grip. More details of the mechanical design of the hand controller can be found in [2].

The main function of the hand controller is twofold: (i) to read the position and orientation of the operator's hand, and (ii) to apply forces and torques to his hand. It can read the position and orientation of the hand grip within a 30 cm cube in all orientations, and can apply arbitrary force and torque vectors up to 20 N and 1.0 NM, respectively, at the hand grip.

A computer-based control system establishes the appropriate kinematic and dynamic control relations between the FRHC and the robot arm controlled by the FRHC. Figure 8.4 shows the FRHC and its basic control system.

The computer-based control system supports four modes of control. Through an on-screen menu, the operator can designate the control mode for each task-space (Cartesian space) axis independently. Each axis can be controlled in position, rate, force-reflecting, and compliant control modes.

Position control mode servos the slave position and orientation to match the master's. Force/torque information from the 6-axis sensor in the "smart hand" generates feedback to the operator of environmental interaction forces via the FRHC. The indexing function allows slave excursions beyond the 1 cubic foot workvolume of the FRHC, and allows the operator to work at any task site from his or her own most comfortable position. This mode is used for local manipulation.

Rate control sets slave endpoint velocity in task space based on the displacement of the FRHC. The master control unit delivers force commands to the FRHC to enforce a "software spring" by which the operator has a better sensation of his or her command, and which provides a zero referenced restoring force. Rate mode is useful for tasks requiring large translations.

Position, Force-Reflecting and Rate modes exist solely on the master side. The slave receives the same incremental position commands in either case. In contrast, variable compliance control resides at the slave side. It is implemented through a low-pass software filter in the hybrid position-force control loop. This permits the operator to control a "springy" or less stiff robot. Active compliance with damping can be varied by changing the filter parameters in the software menu. Setting the spring parameter to zero in the low pass filter will reduce it to a pure damper which results a high stiffness in the hybrid position-force control loop.

The present FRHC has a simple hand grip equipped with a deadman switch and with three function switches. To better utilize the operator's finger input capabilities, an exploratory project evaluated a design concept that would place computer keyboard features attached to the hand grip of the FRHC. To accomplish this, three DATAHAND™ [3] switch modules were integrated with the hand grip as shown in Fig 8.5. Each switch module at a finger tip contains five switches as indicated in Fig 8.6. Thus, the three switch modules at the FRHC hand grip can contain fifteen function keys which can directly communicate with a computer terminal. This eliminates the need for the operator to move his/her hand from the FRHC hand grip to a separate keyboard to input messages and commands to the computer. A test and evaluation, using a mock-up system and ten test subjects, indicated the viability of the finger-tip switch modules as part of a new hand grip unit for the FRHC as a practical step towards a more integrated operator interface device. More on this concept and evaluation can be found in [4].

FRHC CONTROL SYSTEM

An Advanced TeleOperator (ATOP) dual–arm laboratory breadboard system was set up at JPL using two FRHC units in the control station in order to experimentally explore the active role of computers in system operation.

The overall ATOP control organization permits a spectrum of operations between full manual, shared manual and automatic, and full automatic (called traded) control, and the control can be operated with variable active compliance referenced to force-moment sensor data. More on the overall ATOP control system can be found in [5-8]. Only the salient features of the ATOP control system are summarized here. The overall control/information data flow diagram (for a single arm) is shown in Fig. 8.7 . It is noted that the computing architecture of this original ATOP system is a fully synchronized pipeline, where the local servo loops at both the control station and the remote manipulator nodes can operate at a 1000-Hz rate. The end-to-end bilateral (i.e., force-reflecting) control loop can operate at a 200-Hz rate. More on the computational system critical path functions and performance can be found in [9].

The actual data flow depends on the control mode chosen. The different selectable control modes are the following: freeze mode, neutral mode, current mode, joint mode, task mode. In the freeze mode the brakes of joints are locked, the motors are turned off, and some joints are servoed to maintain their last positions. This mode is primarily used when the robot is not needed for a short period of time but turning it off is not desired. In the neutral mode all position gains are set to zero, gravity compensation is active to prevent the robot from falling down. In this mode the user can manually move the robot to any position and it will stay there. In the current mode the six motor currents are directly commanded by the data coming in from the communication link. This mode exists for debugging only. In the joint mode the hand controller axes control individual motors of the robot. In the task mode the inverse kinematic transformation is performed on the incoming data, and the hand controller controls the end effector tip along the three Cartesian and pitch, yaw, and roll axes. This mode is the most frequently used for task execution or experiments, and this is the one shown explicitly in Fig. 8.7.

The control system on the remote site is designed to prevent sudden robot motions. The motion commands received are incremental and are added to the current parameter under control. Sudden large motions are also prevented in case of mode changes. This necessitates proper initialization of the inverse kinematics software at the time of the mode transition. This is done by inputting the current Cartesian coordinates from the forward kinematics into the inverse kinematics.

The data flow diagram shown in Fig. 8.7 illustrates the organization of several servo loops in the system. The innermost loop is the position control servo at the robot site. This servo uses a PD control algorithm, where the damping is purely a function of the robot joint velocities. The incoming data to this servo is the desired robot trajectory described as a sequence of points at 1 ms intervals. This joint servo is augmented by a gravity compensation routine to prevent the weight of the robot from causing a joint positioning error. Because this servo is a first-order servo, there will be a constant position error that is proportional to the joint velocity.

In the basic Cartesian control mode the data from the hand controller are added to the previous desired Cartesian position. From this the inverse kinematics generate the desired joint positions. The joint servo moves the robot to this position. From the actual joint position the forward kinematics compute the actual Cartesian positions. The force-torque sensor data and the actual positions are fed back to the hand controller side to provide force feedback.

This basic mode can be augmented by the addition of compliance control, Cartesian servo, and sticktion/friction compensation. Figure 8 shows the compliance control and the Cartesian servo augmentations. There are two forms of compliance, an integrating and a spring type. In integrating compliance the velocity of the robot end effector is proportional to the force felt in the corresponding direction. To eliminate drift a deadband is used. The zero velocity band does not have to be a zero force, a force offset may be used. Such a force offset is used if, for example, we want to push against the task board at some given force while moving along other axes. Any form of compliance can be selected along any axis independently. In the case of the spring-type compliance the robot position is proportional to the sensed force. This is similar to a spring centering action. The velocity of the robot motion is limited in both the integrating and spring cases.

As is shown in Fig. 8.8, the Cartesian servo acts on task space (X, Y, Z, pitch yaw, roll) errors directly. These errors are the difference between desired and actual task space values. The actual task space values are computed from the forward kinematic transformation of the actual joint positions. This error is then added to the new desired task space values before the inverse kinematic transformation determines the new joint position commands from the new task space commands.

A trajectory generator algorithm was formulated based on observations of profiles of task space trajectories generated by the operators manually through the FRHC. Based on these observations, we formulated a harmonic motion generator (HMO) with a sinusoidal velocity-position phase function profile as shown in Fig. 8.9. The motion is parameterized by the total distance traveled, the maximum velocity, and the distance used for acceleration and deceleration. Both the accelerating and decelerating segments are quarter sine waves, with a constant velocity segment connecting them. This scheme still has a problem, the velocity being zero before the motion starts. This problem is corrected by adding a small constant to the velocity function.

It is noted that the HMG discussed here is quite different from the typical trajectory generator algorithms employed in robotics which use a polynomial position-time function. The HMG algorithm generates the motion as a trigonometric (harmonic) velocity vs position function. More on performance results generated by HMG, Cartesian servo, and force-torque sensor data filtering in compliance control can be found in [6] and [10].

ATOP COMPUTER GRAPHICS

Task visualization is a key problem in teleoperation, since most of the operator's control decisions are based on visual or visually conveyed information. For this reason, computer graphics plays an increasingly important role in advanced teleoperation. This role includes: (i) *planning* actions, (ii) *previewing* motions, (iii) *predicting* motions in real time under communication time delay, (iv) to help operator *training*, (v) to *enable visual perception of non-visible events* like forces and moments, and (vi) to serve as *a flexible operator interface* to the computerized control system.

The capability of task planning aided by computer graphics offers flexibility, visual quality and a quantitative design base to the planning process. The capability of graphically previewing motions enhances the quality of teleoperation by reducing trial-and-error strategies in the hardware control and by increasing the operator's confidence in decision making during task execution. Predicting consequences of motion commands in real time under communication time delay permits longer action segmentations as opposed to the move-and-wait control strategy normally employed when no predictive display is available, increases operation safety, and reduces total operation time. Operator training through a computer graphics display system is a convenient tool for familiarizing the operator with the teleoperated system without turning the hardware system on. Visualization of non-visible effects (like control forces) enables visual perception of different non-visual sensor data, and helps management of system redundancy by providing some suitable geometric image of a multi-dimensional system state. Last, but not least, computer graphics as a flexible operator interface to the control systems replaces complex switchboard and analog display hardware in a control station.

The actual utility of computer graphics in teleoperation to a higher degree depends on the fidelity of graphics models that represent the teleoperated system, the task and the task environment. The JPL ATOP effort was focused at the development of *high-fidelity calibration of graphics* images to actual TV images of task scenes. This development has four major ingredients. First, creation of high-fidelity 3-D graphics models of robot arms and of objects of interest for robot arm tasks. Second, high-fidelity calibration of the 3-D graphics models relative to given TV camera 2-D image frames which cover the sight of both the robot arm and the objects of interest. Third, high-fidelity overlay of the calibrated graphics models over the actual robot arm and object images in a given TV camera image frame on a monitor screen. Fourth, high-fidelity motion control of robot arm graphics image by using the same control software that drives the real robot.

The high fidelity *fused* virtual and actual reality image displays became very useful tools for planning, previewing and predicting robot arm motions without commanding and moving the robot hardware. The operator can generate visual effects of robot motion by commanding and controlling the motion of the robot's graphics image superimposed over TV pictures of the live scene. Thus, the operator can see the consequences of motion commands *in real time,* before sending the commands to the remotely located robot. The calibrated virtual reality display system can also provide high-fidelity *synthetic or artificial* TV camera views to the operator. These synthetic views can make critical motion events visible that otherwise hidden from the operator in a given TV camera view or for which no TV camera view is available. More on the graphics system in the ATOP control station can be found in [11] through [18].

ATOP CONTROL EXPERIMENTS

To evaluate computer-augmented and sensor-aided advanced teleoperation capabilities, two types of experiments were designed and conducted: experiments with *generic* tasks and experiments with *application* tasks. Generic tasks are idealized, simplified tasks and serve the purpose of evaluating some specific advanced teleoperation features. Application tasks are simulating some real-world uses of teleoperation.

In the *generic task experiments*, described in detail in [19], four tasks were used: attach and detach velcro; peg insertion and extraction; manipulating three electrical connector; manipulating a bayonet connector. Each task was broken down to subtasks. The test operators were chosen from a population with some technical background but not with an in-depth knowledge of robotics and teleoperation. Each test subject received 2 to 4 hours of training on the control station equipment. The practice of individuals consisted of four to eight 30-minute sessions.

The generic task experiments were focused at the evaluation of kinesthetic force feedback vs no force feedback, using the specific force feedback implementation techniques of the JPL ATOP project. The evaluation of the experimental data supports the idea that multiple measures of performance must be used to characterize human performance in sensing and computer-aided teleoperation. For instance, in most cases kinesthetic force feedback significantly reduced task completion time. In some specific cases, however, it did not, but it did sharply reduce extraneous forces. More information on the results can be found in [19] and [20].

Two major application task experiments were performed: one *without communication time delay* and one *with communication time delay.*

The experiments without communication time delay were grouped around a simulated satellite repair task. The particular repair task was the duplication of the solar maximum satellite repair (SMSR) mission, which was performed by two astronauts in Earth orbit in the Space Shuttle Bay in 1984. Thus, it offered a realistic performance reference data base. This repair is a very challenging task, because this satellite was not designed for repair. Very specific auxiliary subtasks must be performed (e.g., a hinge attachment) to accomplish the basic repair which, in our simulation, is the replacement of the main electric box (MEB) of the satellite. The total repair, as performed by two astronauts in Earth orbit, lasted for about 3 hours, and comprised the following set of subtasks: thermal blanket removal, hinge attachment for MEB opening, opening of the MEB, removal of electrical connectors, replacement of MEB, securing parts and cables, replug of electrical connectors, closing of MEB, and reinstating thermal blanket. It is noted that the two astronauts were trained for this repair on the ground for about a year.

Several important observations were made during the performance experiments. The two most important observations are that: 1) The remote control problem in any teleoperation mode and using any advanced component or technique is at least 50% a visual perception problem to the operator, influenced greatly by view angle, illumination, and contrasts in color or in shading. 2) The training or, more specifically, the training cycle has a dramatic effect upon operator performance.

The practical purpose of training is, in essence, to help the operator develop a mental model of the system and of the task. During task execution, the operator acts through the aid of this mental model. It is, therefore, critical that the operator understands very well the response characteristics of the sensing and computer-aided ATOP system which has a variety of selectable control modes, adjustable control-gains and scale factors. More on application experiments results can be found in [20], [21] and [22].

The performance experiments with communication time delay, conducted on a large laboratory scale in early 1993, utilized a simulated life-size satellite servicing task which was set up at the Goddard Space Flight Center (GSFC) and controlled 4000 km away from the JPL ATOP control station. Three fixed TV camera settings were used at the GSFC worksite, and TV images were sent to the JPL control station over the NASA-Select Satellite TV channel at video rate. Command and control data from JPL to GSFC and status and sensor data from GSFC to JPL were sent through the Internet computer communication network. The roundtrip command/information time delay varied between 4-8 s between the GSFC worksite and the JPL control station, dependent on the data communication protocol.

The task involved the exchange of a satellite module. This required inserting a 45-cm long power screwdriver, attached to the robot arm, through a 45-cmlong hole to reach the module's latching mechanism at the module's backplane, unlatching the module from the satellite, connecting the module rigidly to the robot arm, and removing the module from the satellite. The placement of a new module back to the satellite's frame followed the reverse sequence of actions.

Four camera views were calibrated for this experiment, entering 15-20 correspondence points in total from three to four arm poses for each view. The calibration and object localization errors at the critical tool insertion task amounted to about 0.2 cm each, well within the allowed insertion error tolerance. This 0.2 cm error is referenced to the zoom-in view (fov = 8 deg) from the overhead (front view) camera which was about 1 m away from the tool tip. For this zoom-in view, the average error on the image plane was typically 1.2-1.6% (3.2-3.4% maximum error); a 1.4% average error is equivalent to a 0.2-cm displacement error on the plane 1 m in front of the camera.

The experiments have been performed successfully, showing the practical utility of high-fidelity predictive-preview display techniques, combined with sensor referenced automatic compliance control, for a demanding telerobotic servicing task under communication time delay. More on these experiments and on the related error analysis can be found in [16] and [17]. Figures 8.9a and 8.9b illustrate a few typical overlay views.

A few notes are in order here regarding the use of calibrated graphics overlays for time-delayed remote control.
1) There is a wealth of computation activities that the operator has to exercise. This requires very careful design considerations for an easy and user friendly operator interface to this computation activity.

2) The selection of the matching graphics and TV image points by the operator has an impact on the calibration results. First, the operator has to select significant points. This requires some rule-based knowledge about what is a significant point in a given view. Second, the operator has to use good visual acuity to click the selected significant points by the mouse.

The following general lessons were learned from the development and experimental evaluation of the JPL ATOP:

1) The sensing, computer- and graphics-aided advanced teleoperation system truly provides new and improved technical features. To transform these features into new and improved task performance capabilities, the operators of the system have to be transformed from naive to skilled operators. This transformation is primarily an undertaking of education and training.

2) To carry out an actual task requires that the operator follow a clear procedure or protocol which has to be worked out off line, tested, modified, and finalized. It is this procedure or protocol following habit that finally will help develop the experience and skill of an operator.

3) The final skill of an operator can be tested and graded by the ability to successfully improve to recover from unexpected errors and complete a task.

4) The variety of I/O activities in the ATOP control station requires workload distribution between two operators. The primary operator controls the sensing and computer-aided robot arm system, while the secondary operator controls the TV camera and monitor system and assures protocol following. Thus, the coordinated training of two cooperating operators is essential to successful use of the ATOP system for performing realistic tasks. It is not yet known what a single operator could do and how. To configure and integrate the current ATOP control station for successful use by a single operator is challenging research and development work.

5) The problem of ATOP system development is not only to find ways to improve technical components and to create new subsystems. The final challenge is to integrate the improved or new technical features with the natural capabilities of the operator through appropriate human-machine interface devices and techniques to produce an improved overall system performance capability in which the operator is part of the system in some new way. Figure 10 illustrates in a summary view the machine environment of the JPL ATOP control station.

ANTHROPOMORPHIC TELEROBOTICS

The use of a robot arm of the industrial type with industrial type parallel claw end effectors sets definite limits for the arm's task performance capabilities as dexterity in manipulation resides in the mechanical and sensing capabilities of the hands (or end effectors). The use of industrial-type arms and end effectors in space would essentially require to design space manipulation tasks matching the capabilities of industrial-type arms and end effectors. Contrary to that, existing space manipulation tasks (except the handling of large space cargos) are designed for astronauts, including the tools used by astronauts. There are well over three hundred tools that are available today and certified for use by Extra Vehicular Activity (EVA) astronauts in space. Motivated by these facts, an effort parallel to the ATOP project was initiated at JPL to develop and evaluate human-equivalent or human-rated dexterous telemanipulation capabilities for potential applications in space because all manipulation related tools used by EVA astronauts are human rated.

The actual design and laboratory prototype development included the following specific technical features: 1) the system is fully electrically driven; 2) the hand and glove have four fingers (little finger is omitted) and each finger has four DOF; 3) the base of the slave fingers follow the curvature of the human fingers' base on the hand; 4) the slave hand and wrist form a mechanically integrated closed subsystem, that is, the hand cannot be used without its wrist; 5) the lower slave arm which connects to the wrist houses the full electromechanical drive system for the hand and wrist (altogether 19 DOF), including control electronics and microprocessors; and 6) the slave drive system electromechanically emulates the dual function of human muscles, namely, position and force control. This implies a novel and unique implementation of active compliance. All of the specific technical features taken together make this exoskeleton unique among the few similar systems. No other previous or ongoing developments have all the aforementioned technical features in one integrated system, and some of the specific technical features are not represented in any other similar systems at all. More on this system can be found in [23] and [24].

The JPL anthropomorphic telemanipulation system was assembled and tested in a *terminus control configuration*. In this configuration the master glove is integrated with previously developed nonanthropomorphic six-DOF force-reflecting hand controller (FRHC), and the mechanical hand and forearm are mounted to an industrial robot (PUMA 560), replacing its standard forearm. The notion of terminus control mode refers to the fact that only the terminus devices (glove and robot hand) are of anthropomorphic nature, and the master and slave arms are nonanthropomorphic.

The system is controlled by a high-performance distributed computer controller. Control electronics and computing architecture were custom developed for this telemanipulation system.

The anthropmorphic telemanipulation system in terminus control configuration is shown in Fig. 11. The master arm/glove and the slave arm/hand have 22 active joints each. The manipulator lower arm has five additional drives to control finger and wrist compliance. This active electromechanical compliance (AEC) system provides the muscle equivalent dual function of position as well as stiffness control. A cable links the forearm to an overhead gravity balance suspension system, relieving the PUMA upper arm of this additional weight. The forearm has two sections, one rectangular and one cylindrical. The cylindrical section, extending beyond the elbow joint, contains the wrist actuation system. The rectangular cross section houses the finger drive actuators, all sensors, and the local control and computational electronics. The wrist has three DOF with angular displacements similar to the human wrist. The wrist is linked to an AEC system that controls the wrist's stiffness. It is noted again that the slave hand, wrist, and forearm form a mechanically closed system, that is, the hand cannot be used without its wrist. A glove-type device is worn by the operator. Its force sensors enable hybrid position/force control and compliance control of the mechanical hand. Four fingers are instrumented, each having four DOF. Position feedback from the mechanical hand provides position control for each of the 16 glove joints. The glove's feedback actuators are remotely located and linked to the glove through flex cables. One-to-one kinematic mapping exists between the master glove and slave hand joints, thus reducing the computational efforts and control complexity of the terminus subsystem. The exceptions to the direct mapping are the two thumb base joints which need kinematic transformations.

The system was successfully tested on eighteen astronaut equivalent tool handling tasks. It became clear during the tests, however, that many EVA tool handling task require a dual-arm fingered hand system with four fingers and with 7-DOF compliant robot arms. The tests also demonstrated the distinct advantages of the terminus control configuration in anthropomorphic telemanipulation as compared to a fully exoskeleton master arm configuration.

NEW TRENDS IN APPLICATIONS

Applications of teleoperators or telerobots are numerous, in particular in the nuclear and munitions industries, maintenance and reclaiming industries operating in hostile environments, and in industries that support space and underwater operations and explorations. Lately, robotics and teleoperation technology started breaking ground also in the medical field. Diagnostic and actual operative surgeries, including microsurgery and telesurgery within the general frame of telemedicine, seem to be receptive fields for potential use of robotic and teleoperator tools and techniques.

An interesting Robot Assisted MicroSurgery (RAMS) telerobotic workstation was developed at JPL recently in collaboration with Steve Charles, MD, a vitreo-retinal surgeon. RAMS is a prototype system that will be completely under the manual control of a surgeon. The system, shown in Figure 8.12a and 8.12b, has a slave robot that will hold surgical instruments. The slave robot motions replicate in six degrees of freedom those of the surgeon's hand measured using a master input device with a surgical instrument shaped handle. The surgeon commands motions for the instrument by moving the handle in the desired trajectories. The trajectories are measured, filtered, and scaled down, and then used to drive the slave robot.

The RAMS workstation is a 6-d.o.f master-slave telemanipulator with programmable controls. The primary RAMS control mode is telemanipulation, which includes task-frame referenced manual force feedback and textural feedback. The operator is also able to interactively designate or "share" automated control of robot trajectories. RAMS not only refines the physical scale of state-of-art microsurgical procedures, but also enables more positive outcomes for average surgeons during typical procedures — e.g., the RAMS workstation controls include features to enhance manual positioning and tracking in the face of myoclonic jerk and tremor that limit most surgeons' fine-motion skills. More on RAMS can be found in [25] and [26].

ACKNOWLEDGMENT

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TABLE and FIGURES CAPTIONS
(A. K. Bejczy's Subsection)

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Table 8.1 - Tradeoff and Value Analysis of Handle Designs (1: lowest, 3: highest ratings)

	ENGINEERING DEVELOPMENT				CONTROLL-ABILITY		HUMAN-HANDLE INTERACTION				HUMAN LIMITA-TIONS		
	DESIGN SIMPLICITY	DIFFICULTY OF IMPLE-MENTATION	TECHNOLOGY BASE	COST	STIMULUS-RESPONSE COMPATIBILITY	CROSS COUPLING	SECONDARY-FUNCTION CONTROL	FORCE FEEDBACK	KINESTHETIC FEEDBACK	ACCIDENTAL ACTIVATION	ENDURANCE CAPACITY	OPERATOR ACCOMMODATION	TOTAL FIGURE OF MERIT Σ VALUE X SCORE
VALUE	2	1	5	4	3	5	5	4	4	4	3	2	
A) INDUSTRY STANDARD	2	2	3	2	3	3	1	3	3	2	1	2	97
B) ACCORDIAN	3	3	1	3	2	1	3	3	3	3	2	2	98
C) FULL-LENGTH TRIGGER	2	2	3	2	2	1	3	3	3	3	2	2	101
D) FINGER TRIGGER	3	3	3	3	2	3	3	2	3	3	3	2	117
E) GRIP BALL	3	3	2	2	2	3	1	2	2	1	2	3	85
F) BIKE-BRAKE	3	3	3	3	2	1	3	3	3	3	2	2	108
G) POCKET KNIFE	3	3	3	3	2	1	3	3	3	3	2	2	108
H) PRESSURE NUB	3	3	1	3	1	1	1	1	1	1	1	3	60
I) T-BAR	3	3	3	3	2	3	1	2	2	1	2	3	94
J) CONTOURED	2	2	1	2	1	1	3	1	1	2	1	3	67
K) GLOVE	1	1	1	1	3	3	1	3	3	2	2	1	81
L) BRASS KNUCKLE	2	2	3	2	2	1	3	3	3	2	2	3	99
M) DOOR HANDLE	3	3	3	3	2	3	2	2	2	2	2	3	103
N) AIRCRAFT GUN TRIGGER	3	3	3	3	2	3	1	2	2	1	2	3	94

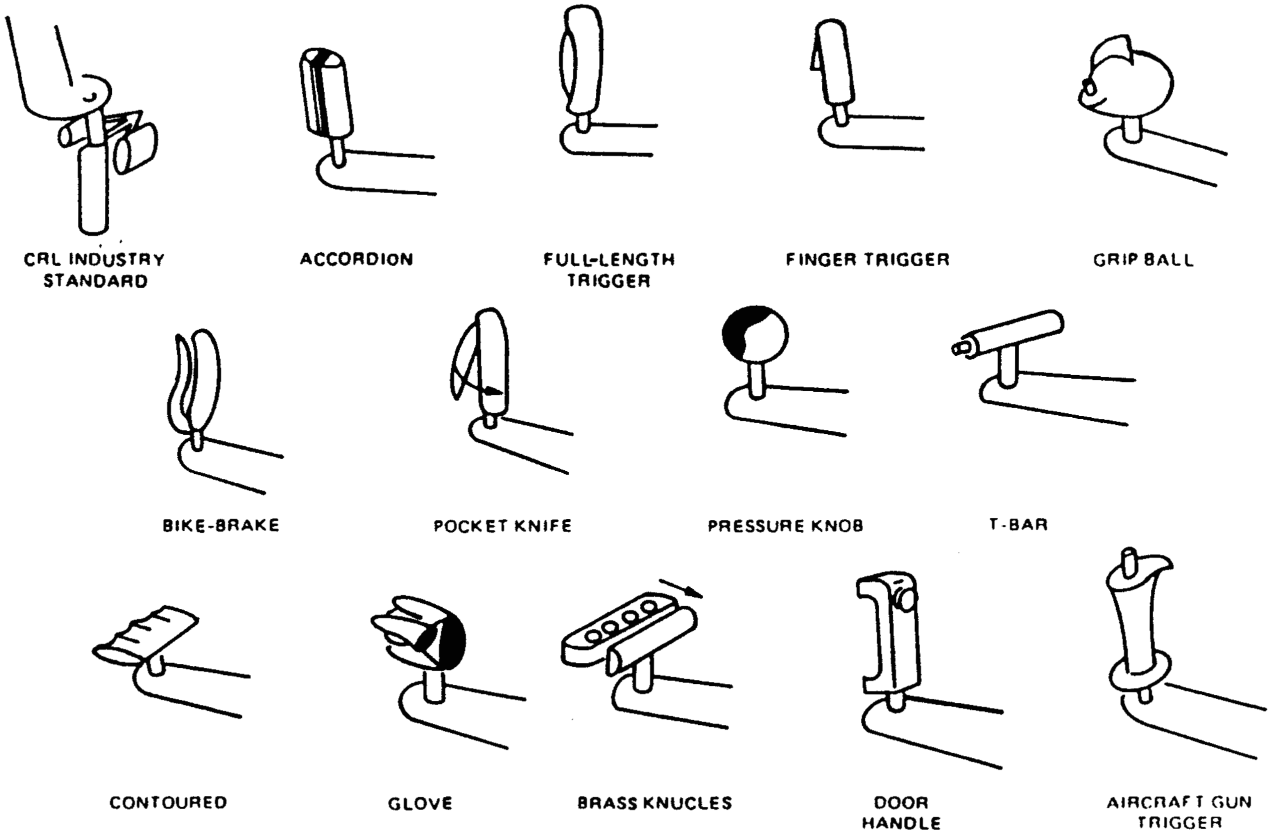

Figure 8.1 - Basic Grip and Trigger Concepts

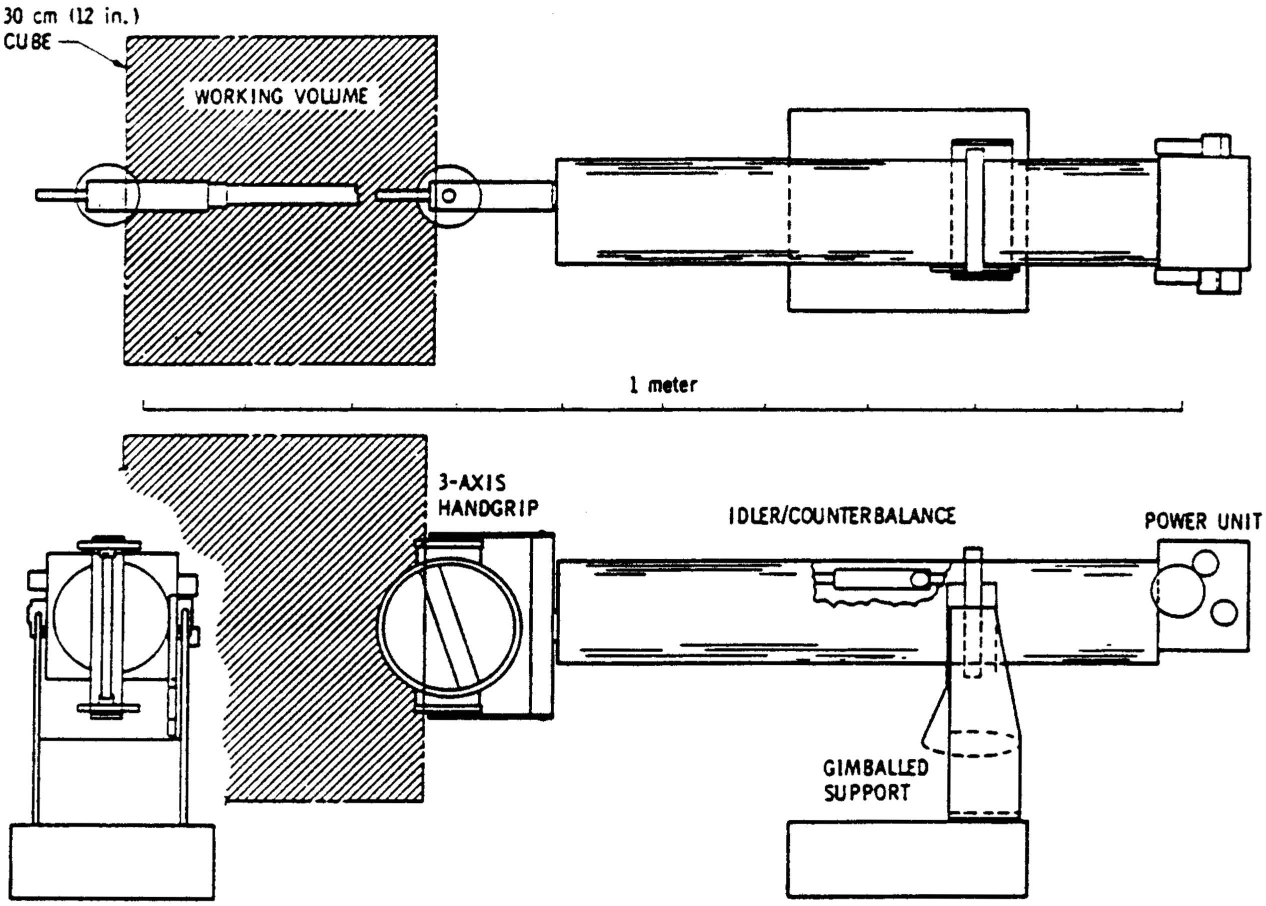

Figure 8.2 - Six-Axis Force-Reflecting Hand Controller Overall Schematic

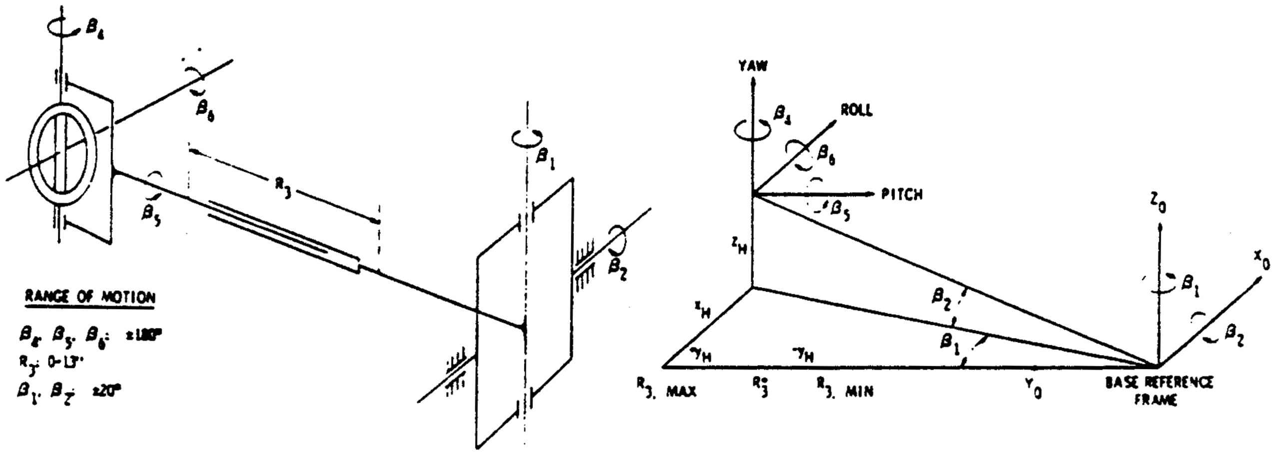

Figure 8.3 - Hand Controller Kinematics and Command Axes

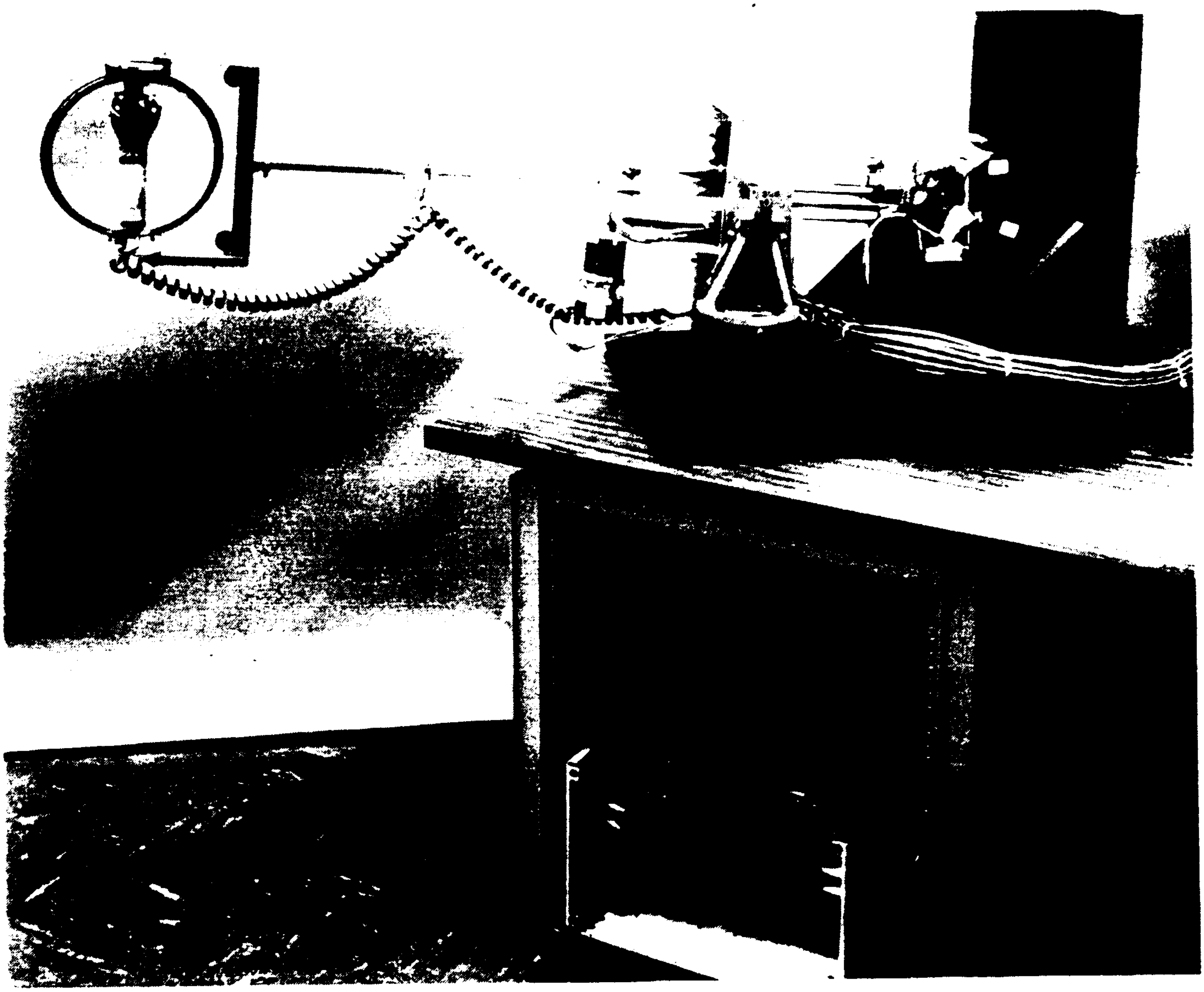

Figure 8.4 - "Universal" Force-Reflecting Hand Controller with Basic Computer Control System

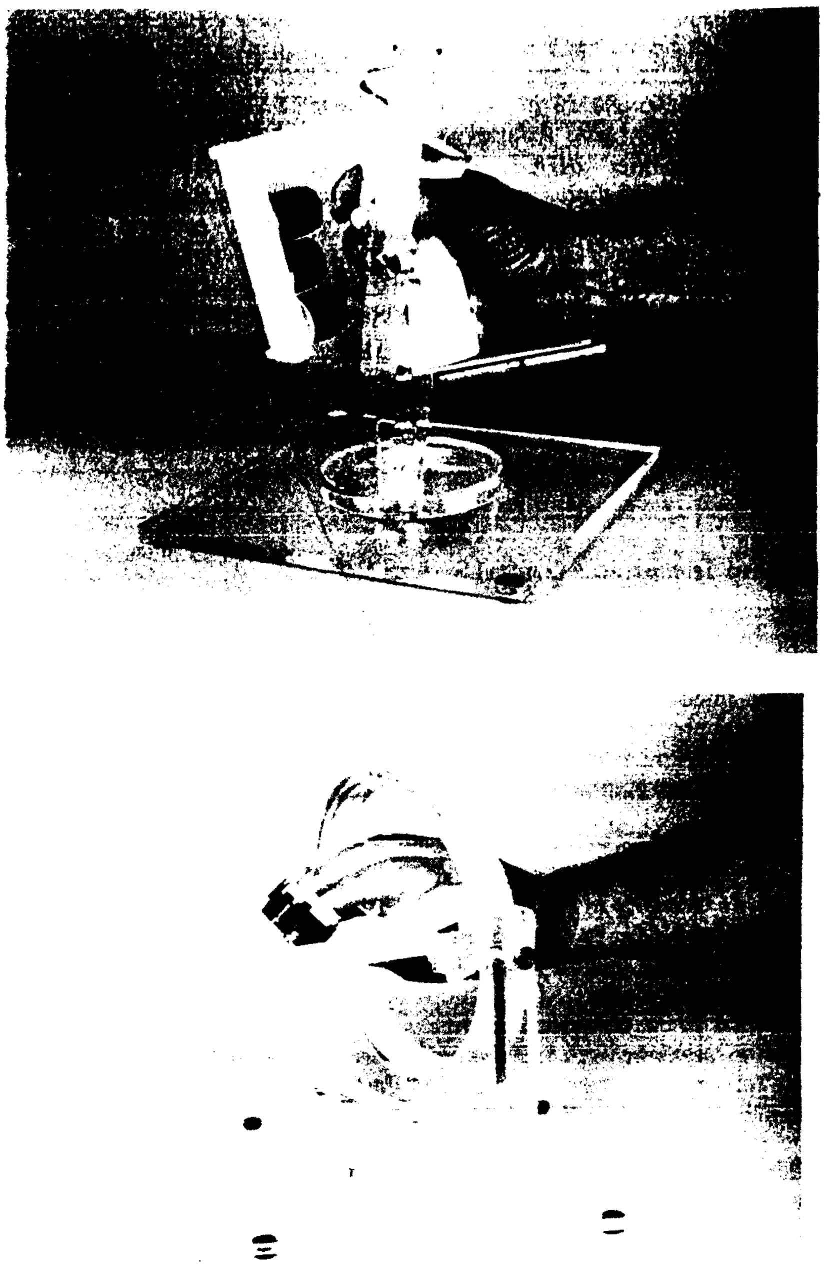

Figure 8.5 - DATAHAND™ Switch Modules Integrated with FRHC Hand Grip

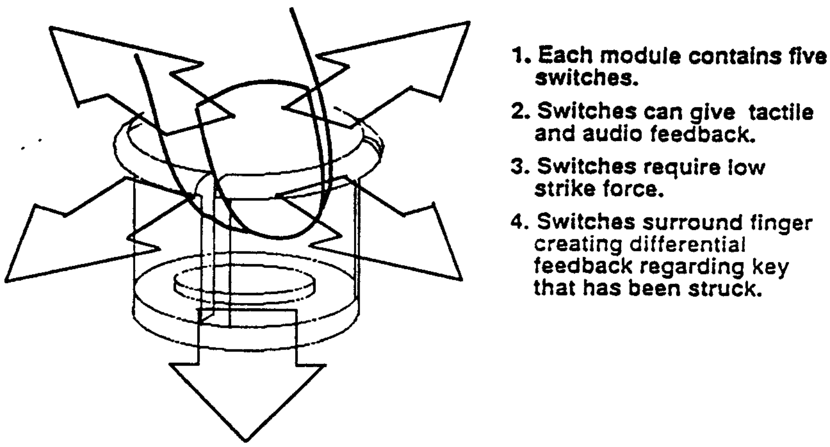

Figure 8.6 - Five Key-Equivalent Switches at a DATAHAND™ Fingertip Switch Module

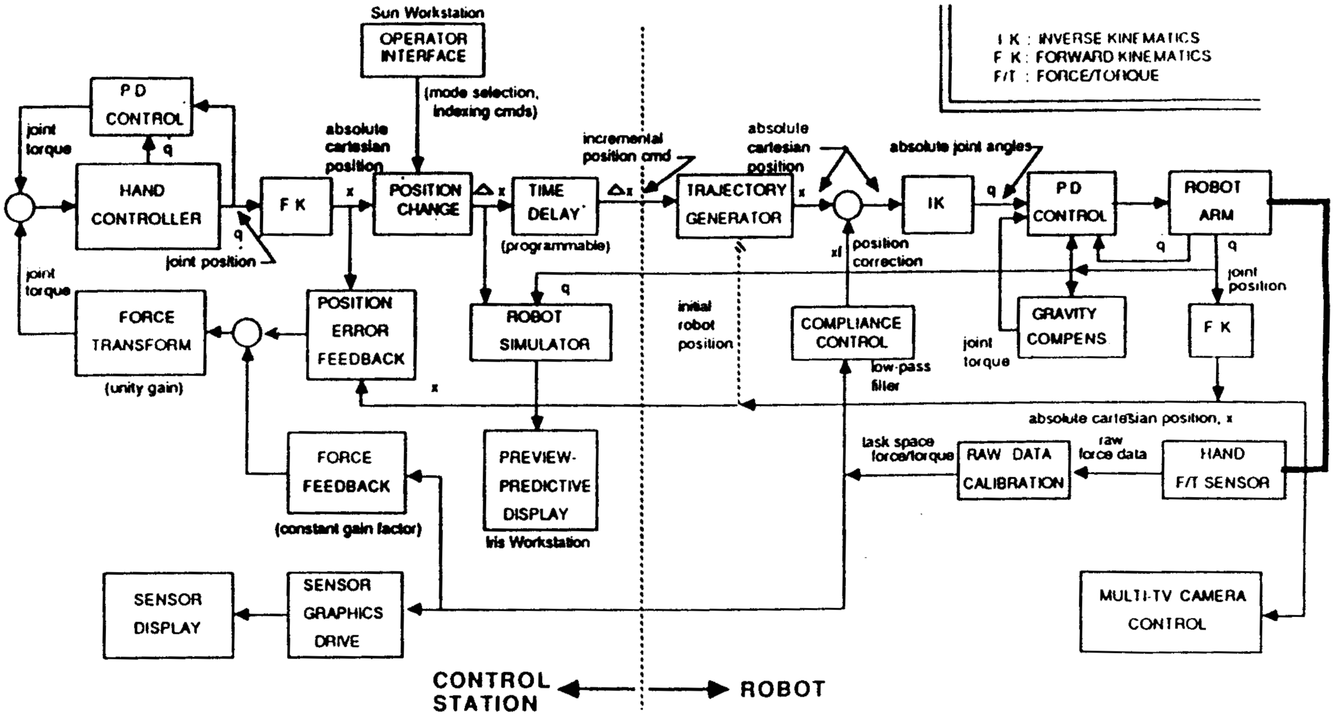

Figure 8.7 - Control System Flow Diagram

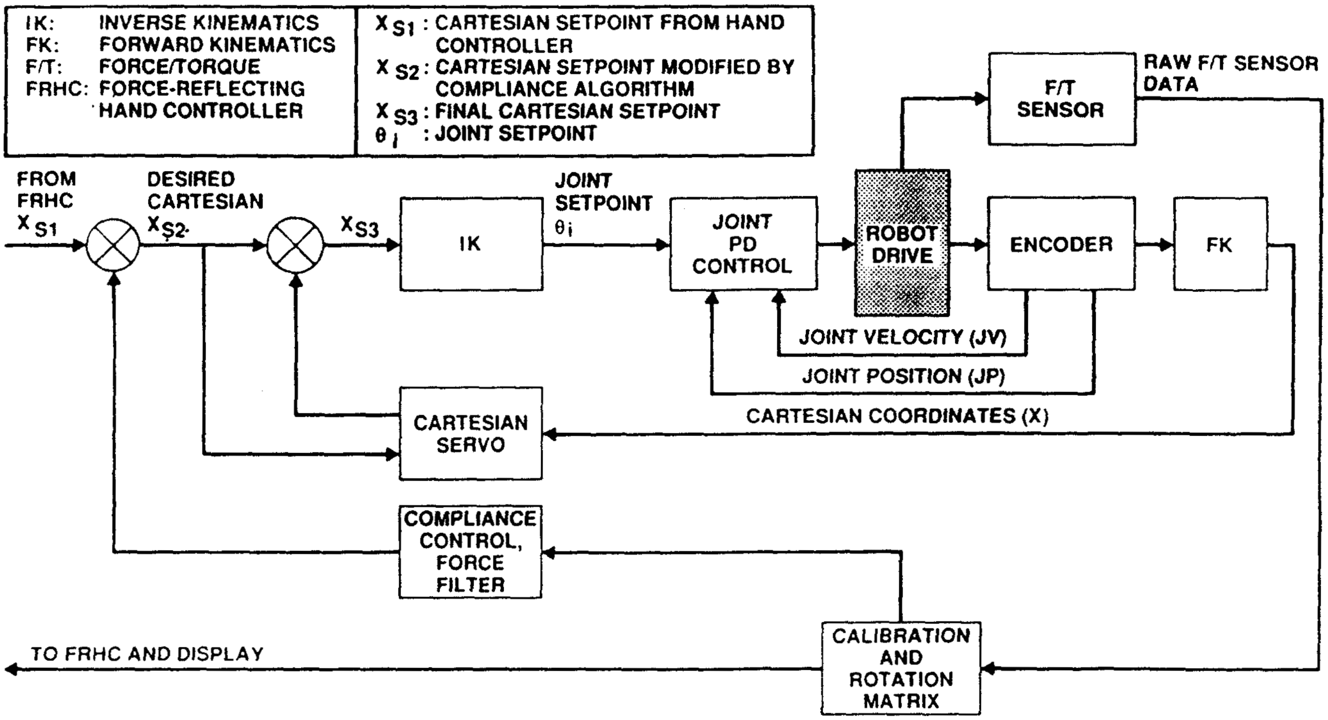

Figure 8.8 - Control Schemes: Joint Servo, Cartesian Servo, Compliance Control

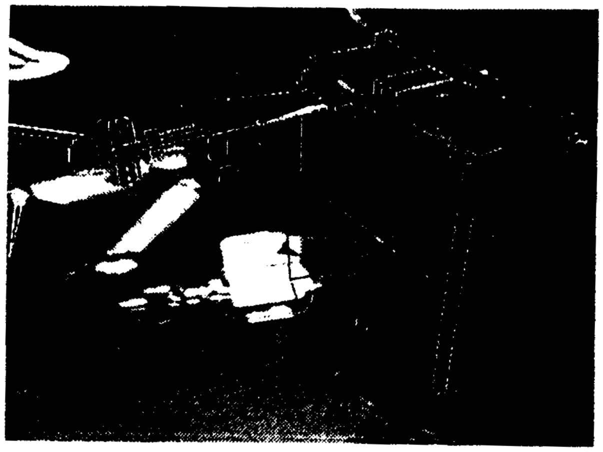

Figure 8.9a - Predictive/Preview Display of End Point Motion

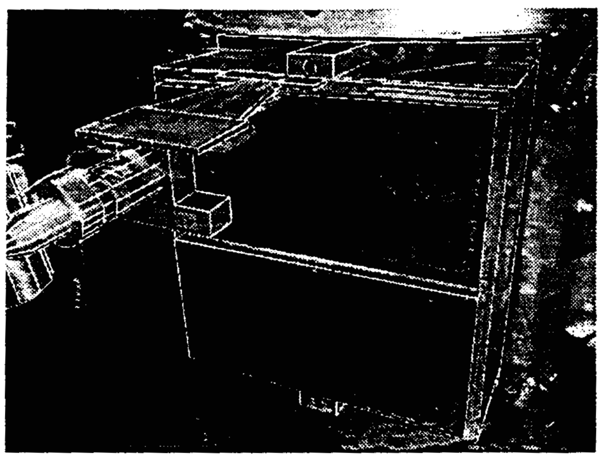

Figure 8.9b - Status of Predicted End Point After Motion Execution, from a TV Camera View Different from the View Shown in Fig. 8.9a

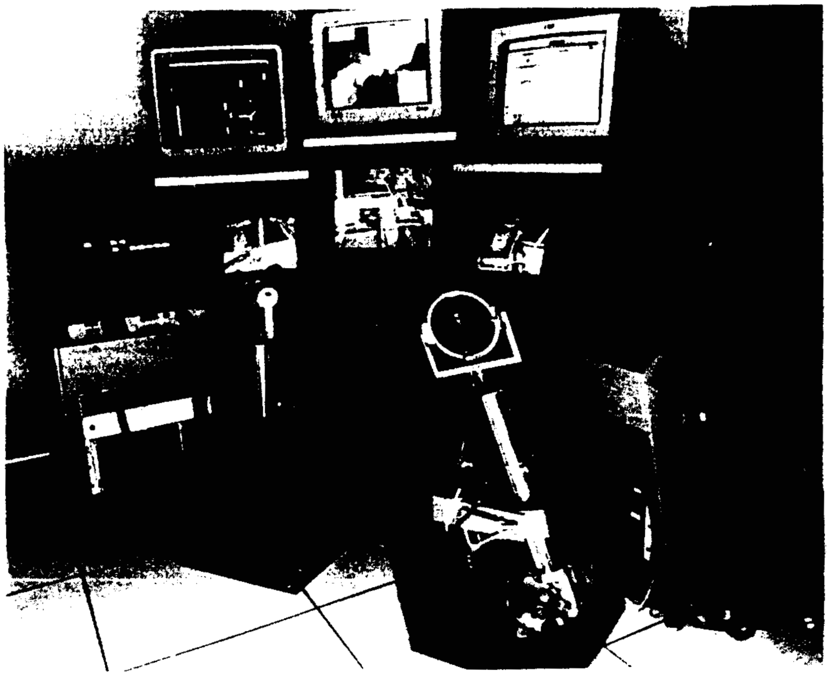

Figure 8.10 - JPL ATOP Control Station

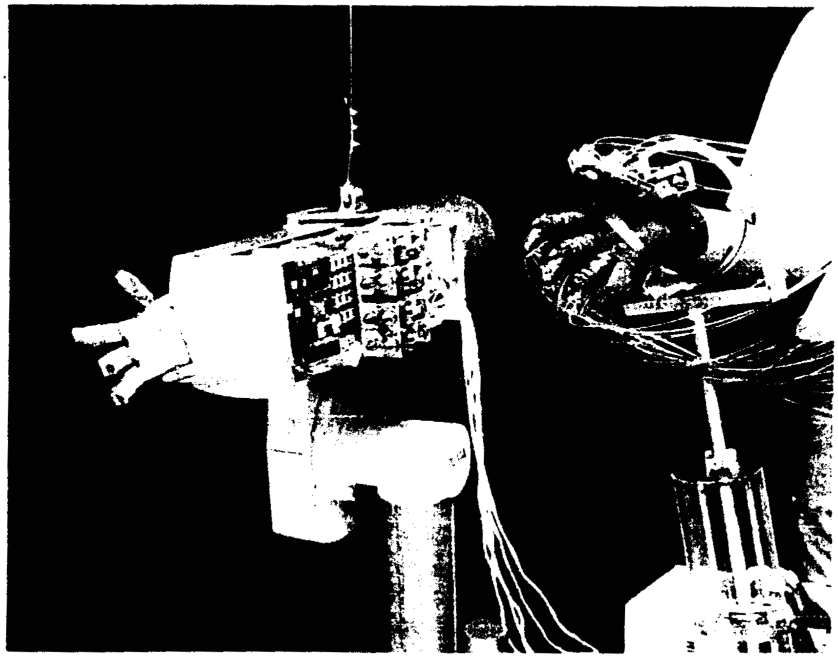

Figure 8.11 - Master Glove Controller and Anthropomorphic Hand

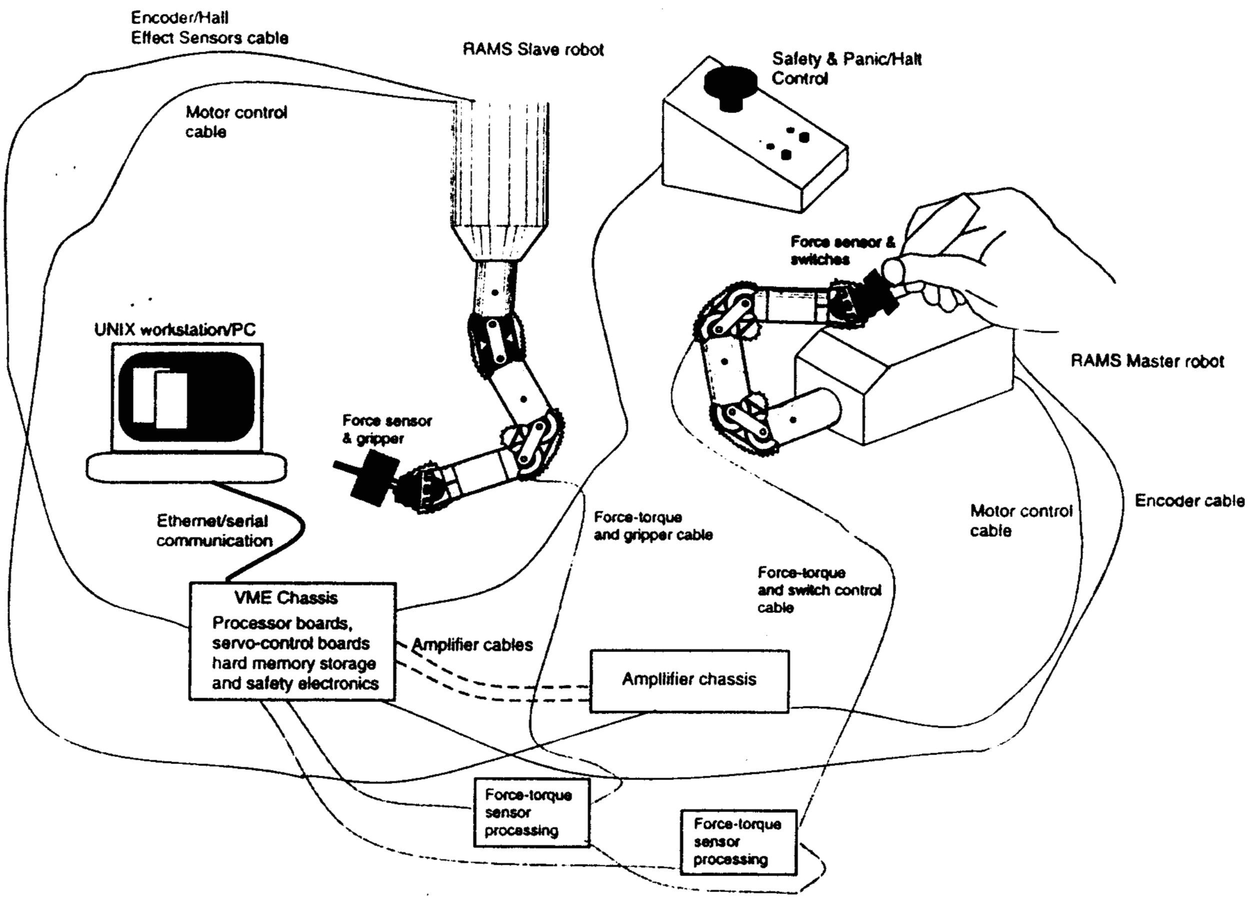

Figure 8.12a - RAMS Master - Slave System Schematic

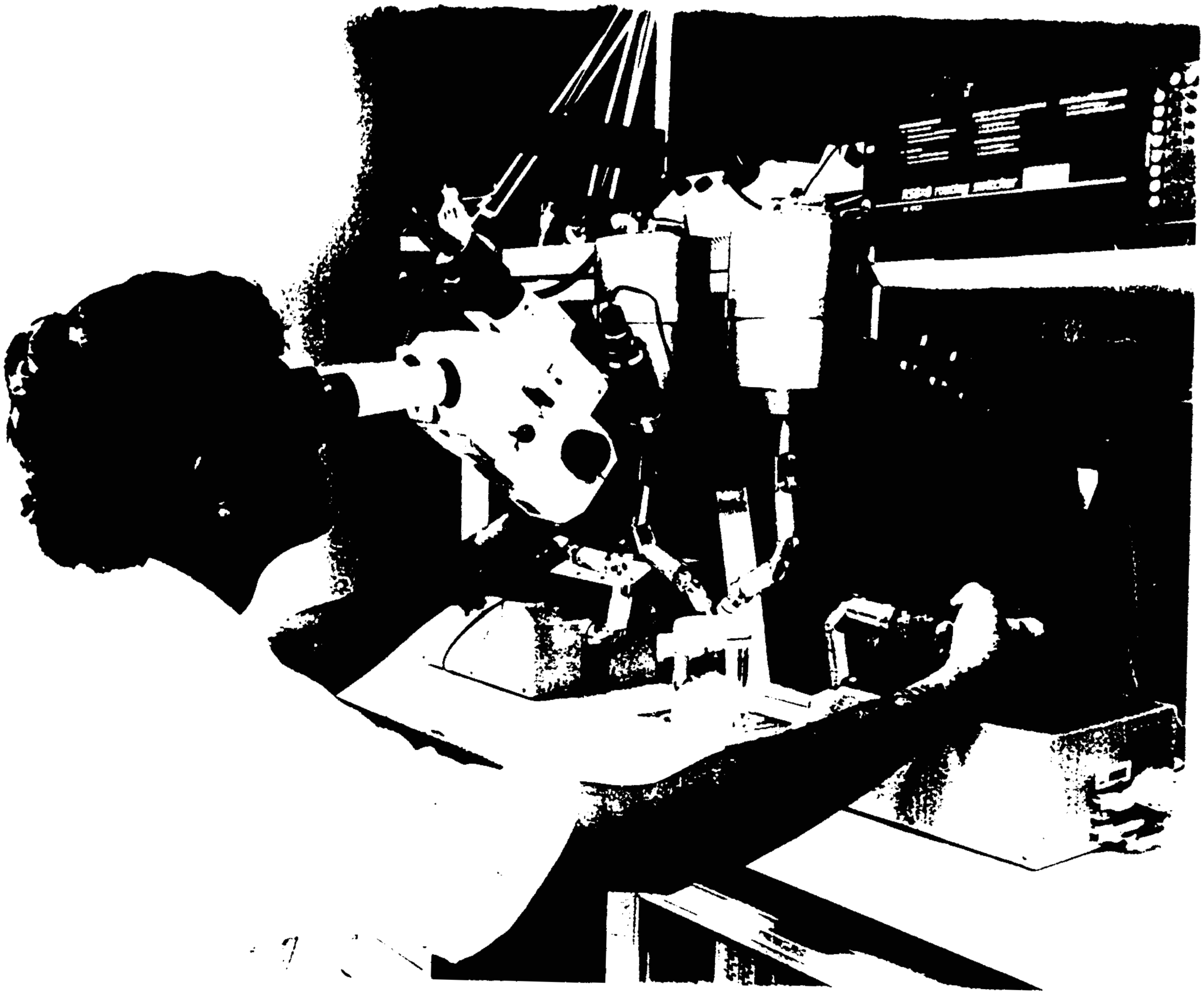

Figure 8-12b - Fine Suturing Test with Two-Handed RAMS System